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Review and modelling the systems of transmission concentrated solar energy via optical fibres

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Abstract

The aims of this study are to optimize the coupling of a low-cost offset paraboloidal dish, which concentrates direct solar irradiance with dual axes tracking component, and the fibre optic bundle (FOB), which transmits concentrated solar energy; to review previous studies on the transmission of concentrated solar energy via optical fibres (TCSEvOF) by classifying according to their purposes; to present a mathematical model for coupling symmetrical paraboloidal dish and FOB, and a modified model for optimum coupling of offset paraboloidal dish proposed in our study, taking into account the parameters of the dish and dispersion effect; to apply the models to symmetrical and offset paraboloidal dish under the same conditions; and to compare the annual output power obtained. Optical efficiency of the whole system was calculated as 68% in optimum condition, but it was found to be 63% for the system proposed. Overall system efficiency was found to be 59%. It was found that offset paraboloidal dish produced much more energy than the symmetrical one does when comparing under the same conditions. The difference of monthly average annual obtainable power was calculated as 0.82%. The monthly average annual power gained from the offset paraboloidal dish proposed was computed as 1041.6 kW to per square metre.

Keywords: Optimization; Coupling; Offset paraboloidal concentrator; Fibre optic bundle

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Abbreviations: NA, numerical aperture (dimensionless); FOB, fibre-optic bundle; TCSEvOF, transmission of concentrated solar energy via optical fibres; CPC, compound parabolic concentrator; POFs, plastic optical fibres; TROF, tower reflector with optical fibres; EU-SEI, Ege University Solar Energy Institute; LDR, light-dependent resistance

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1. Introduction

Mitigating climate change and achieving stabilization of greenhouse gas atmospheric concentrations—the objective of the United Nations Framework Convention on Climate Change—will require deep reductions in global emissions of energy-related carbon dioxide emissions. Developing and disseminating new, low-carbon energy technology will thus be needed [1].

Energy is the key to industrial development for the promotion of economic and social well-being of the world population. The rapid depletion of fossil-fuel resources on a worldwide basis has necessitated an urgent search for alternative energy sources to meet our demands for the immediate future and for generations to come [2]. The sun is the unique inexhaustible energy source, not including smoke, CO, SO_2 and other pollutants, has very small operating cost, and gives opportunities for solutions of various applications, is not affected economically and politically, thanks to the independency of the other countries. A solar system should try to discover to provide the optimal combination of efficient performance, low initial and operation costs, robustness and durability.

The idea of transmission of concentrated solar energy via optical fibres (TCSEvOF) was put forward in 1980 by a group of French investigators. Owing to the unavailability of high-quality optical fibres and the high cost of their design, this project limited itself to theoretical analysis only. With the present-day availability of fibre-optic techniques, solar energy can be transmitted by high-quality optical fibres of large core diameter and large numerical aperture [3–5].

TCSEvOF systems provide flexible options for numerous implementations such as solar lighting, solar power generation, solar surgery, photobioreactors, hydrogen generation and photochemical reactions and solar pumped lasers.

A paraboloidal concentrator produces the image of Sun and high-density radiation on its focal point. The concentrator and bundle components must be integrated properly to transfer the solar energy completely and efficiently. There is a relationship between dish parameters and image size on the focal point. It is critically important to size and optimize dish parameters such as aperture diameter, rim angle, focal length and diameter and location of FOB. In this study, it is aimed to optimize the coupling of a low-cost offset paraboloidal dish, which concentrates direct solar radiation with two axes tracking component, and the fibre optic bundle (FOB), which transmits concentrated solar energy. Optical considerations and steps of transferring energy were mathematically modelled for a non-symmetrical, low cost and high reflective offset paraboloidal dish, transformed from a simple satellite antenna and processed to chromize.

The main objectives in carrying out the present study are (i) to review previous studies on TCSEvOF by classifying according to their purposes; (ii) to present a mathematical model for coupling symmetrical paraboloidal dish and FOB and a modified model for the optimum coupling of offset paraboloidal dish proposed in the present study, taking into account the parameters of the dish and dispersion effects; and (iii) to apply the models to symmetrical and offset paraboloidal dishes under the same conditions and to compare the annual output power obtained from the systems.

The structural organization of this study can be listed as follows. In Section 1, a brief introduction is given by emphasizing the aims of this study. A classified review covered by six different titles listed as characterization of the system, solar lighting, solar surgery, photo-bio reactors, hydrogen generation and photochemical reactions, solar power generation and solar pumped lasers is presented in Section 2. The contributions and the originalities of the present study are also emphasized in Section 2. Mathematical models for both symmetrical and offset paraboloidal dishes and the system proposed are discussed in Section 3, while the data used for calculation, the results from the models and some economical aspects of the low-cost offset paraboloidal dish and its capital and operation costs are discussed in Section 4. Finally, the last section concludes the paper, compares the advantages and disadvantages of the symmetrical and offset dishes, and emphasizes some important suggestions for future works.

2. An overview of the previous studies

studies conducted before on TCSEvOF for various purposes can be grouped by six main titles. It can be listed as follows: characterization of the system, solar lighting, solar surgery, photobioreactors—hydrogen generation and photochemical reactions, solar power generation and solar pumped lasers. An overview of these studies is given under classified titles as below.

2.1. Characterization of the system

Cariou et al. [5] investigated the transmission properties of fibres as well as the geometrical conditions of the association between fibres and concentrators. It was shown that modules where one fibre is associated with a small

Nomenclature

n_1	refraction index of the core material (dimensionless)
n_2	refraction index of the cladding material (dimensionless)
$\dot{Q}_p$	energy rate on the focal point (W)
f	focal length (m)
G_b	solar beam irradiance (W/m^2)
D_a	aperture diameter (m)
D_r	receptor diameter (m)
D_{of}	fibre-optic bundle diameter (m)
f_o	optimal focal length (m)
$\dot{Q}_{i,of}$	energy rate at the inlet of the optical fibre bundle (W)
$\dot{Q}_{o,of}$	energy rate at the end of the optical fibre bundle (W)
A_{of}	fibre-optic bundle area (m^2)
A_a	aperture area (m^2)
F_s	view factor (dimensionless)
C_{max}	maximum ratio of geometrical concentration (dimensionless)
L	fibre-optic bundle length (m)
dB_{loss}	decibel loss/attenuation of optical fibre (dB/km)
d_{min}	focal spot diameter for uniform-flux core region (m)
d_{max}	maximum focal spot diameter (m)
g_{max}	combined expression of the view factor and concentration ratio (dimensionless)

Greek letters

α	angle for offset paraboloidal dish (0)
δ	dispersion angle (0)
θ_{max}	admission/acceptance angle (0)
ϕ_r	paraboloidal dish rim angle (0)
ϕ_s	paraboloidal dish shading angle (0)
ρ_m	reflectivity of the paraboloidal dish (dimensionless)
η_{FOB}	efficiency of the fibre-optic bundle (dimensionless)
$\eta_{o,opt}$	optimum optical efficiency (dimensionless)
η_s	overall system efficiency (dimensionless)

parabolic mirror may supply 2 W with an efficiency greater than 70%, while the concentration on the exit end of a 10-m-long fibre may exceed 3000 [5].

Dugas et al. (1985) predicted what may be expected in solar furnaces making use of optical fibres, taking into account the possibility of transport of concentrated solar energy using fibres. It was considered that the ideal case was where a spherical or a cylindrical receiver is surrounded by an enclosure consisting entirely of fibre ends. It was concluded that very high temperatures may be reached. It was shown that, in a more practical case where the receiver is a reflective enclosure in which there are fewer fibre ends, temperatures higher than 1500 °C may be reached while maintaining very good efficiency. Such furnaces have the extra advantage of having temperature gradients, which may be perfectly determined [6].

Khatri et al. [7] discussed a solar energy collection system in which optical fibres are used to transport energy from a single-stage and a double-stage, three-dimensional compound parabolic concentrator (CPC). After developing a thermo-mathematical model for the assembly of CPC and fibres, numerical simulations were used to optimize the system design. The modules filled with plastic and glasses were shown to perform considerably better than those filled with air. It was found that a two-stage system performs better than a single-stage module. CPC surface reflectance improves the yield but an increase in fibre length decreases the performance [7].

Liang et al. [3] emphasized that the high flux solar energy transmission by a flexible fibre-optic bundle and the research on the associated CPC would largely expand the existing field of applications of solar energy concentrators. It was reported on a flexible light guide that consists of 19 optical fibres and is capable of transmitting up to 60 W of optical power, with 60% efficiency [3].

Gordon et al. (1999) proposed a model that offers substantial advantages in efficiency, compactness, reduced mechanical loads, and ease of fabrication and installation relative to conventional solar designs, a new concept for efficient solar energy concentration and power delivery. The design included the availability of low-attenuation optical fibres, as well as the practical advantages of mass-producing highly accurate very small parabolic dishes. The system's building block was a miniature (e.g. 0.2 m diameter) solar dish, which concentrates sunlight into a single optical fibre. It was indicated that systems are modular and can be employed in central power generation, ranging from a few kilowatts to tens of megawatts. Designs for maximum efficiency attaining collection efficiencies as high as 80%, and maximum-concentration designs realizing flux levels of 30 000 suns, are achievable [8]. Also Gordon et al. [22,23] showed that optical fibres used to transport sunlight exhibit considerable light leakage within their nominal numerical aperture and this leakage depends on (a) the incidence angle, (b) the optical properties of the core and the cladding and (c) fibre length [9].

Jaramillo et al. [10] presented a model based on Maxwell's equations and the Drude–Lorentz theory to determine the non-linear absorption for the maximum possible concentration ratio for circular concentrators. The relation between the electric susceptibility and the refractive index with microscopic parameters was provided. To solve the non-linear model for absorption, experimental parameters were used. It was estimated that the average

value over the solar spectrum for the non-linear extinction coefficient for SiO_2 is $k = 10^{-29}\,m^2\,V^{-2}$. With this result it was concluded that the non-linear part of the absorption coefficient of SiO_2 optical fibres during the transport of concentrated solar energy achieved by a circular concentrator is negligible [10].

Johnston et al. [11] stated that while paraboloidal dishes have traditionally been used for high-flux/high-power solar concentration devices, the manufacture of multi-facet collectors has been complicated somewhat by the need to produce reflecting elements having different curvatures for different regions of the paraboloidal surface. It was indicated that this complication could be minimized using identical spherical reflector sub-components mounted with a paraboloidal orientation on a space frame dish structure. It was compared with the optical performance and manufacturing feasibility of collectors having such a combination of surfaces [11].

Nagai [12] analysed a divergence angle of the light emanating from an optical source composed of a source of light with finite size and a paraboloidal reflector on the basis of geometrical considerations. The divergence angle distributions of the reflected light rays from each reflection point on the paraboloidal mirror were numerically calculated as parameters of the shapes of a lamp arc body and a paraboloidal reflector. It has been found from the analyses that the divergence angle can be reduced by prolongation of the optical path length PO to the reflection point P on the paraboloidal mirror from its focal point O, at which the centre of the extent of the arc is located. A new approach different from the conventional one was proposed, in order to reduce the divergence angle of the light rays emanating from the optical source. The new configurations of the optical source composed of a light source with finite size and a paraboloidal reflector or a spheroidal converging reflector are shown and discussed [12].

Luca [13] studied light ray paths in an optical fibre with a conic hole at one of its extremes by means of geometrical optics, with the aim of transferring the maximum amount of radiant energy from a concentrated light source to a solar trap. It was indicated that this particular application can be useful in sunlight-collecting systems, which are can concentrate light rays in a spot of small dimensions [13].

Liu et al. [14] analysed the random surface error, tracking error, position error and shadow of the receiver of parabolic dish concentrators by using the ray tracing and the Monte-Carlo method. It was noted that the analysis could help in optimizing the system efficiency and in measuring the flux density distribution [14].

2.2. Solar lighting

Ciamberlini et al. [15] described an innovative architecture for the exploitation of the whole collected solar energy. A sun-pointing optical concentrator focuses the received energy, containing a part of the required solar spectrum, in a low-loss optical fibre transmission line. The optical panel is small in size and can follow the sun in order to collect maximum energy. The support is flat, 5 mm thick and includes four optical concentrators. It was noted that the efficiency of the optical system depends on the optical configuration and on the material used for the optical components. The system was experimented for lightning, during the day, dissipated in a dark load in order to produce heat in some equipment and for photovoltaic applications. It was found that the total efficiency of the system was between 68% and 72% [15].

Schlegel [16], Burkholder [17] and Cheadle [18] studied in depth the hybrid lighting system, in which the concentrated visible light is distributed through optical fibres and combined with fluorescent lighting in specially designed luminaries. A simulation of a hybrid lighting system has been created using the "TRNSYS" transient simulation programme. The simulation incorporates the spectral properties of the hybrid lighting components as well as the spectral distribution of the incoming solar radiation that is based on the output from the SMARTS atmospheric transmittance model. Simulations were performed in six locations within the United States. Hybrid lighting systems performed best in Honolulu, HI and Tucson, AZ justifying system capital costs of \$2410 and \$1995 per module, respectively, based on a 10-year payback period. Thermal management in FOB was discussed. The colour properties of the hybrid lighting system were evaluated with artificial light sources and were estimated to be between 5000 and 5500 K [16–19].

Tsangrassoulis (2005) [20] presented a method to control the light output from a prototype hybrid lighting system. The control strategy is based on cloudiness prediction. It is emphasized that the time evolution of the cloud cover would determine whether one or both lamps should be switched on or off. Lighting energy savings were found to be equal to 55.4% for January and 58.8% for June sky conditions of Athens.

2.3. Solar surgery

The spectral properties of both biological tissue and available optical fibres render visible and near-infrared lasers as best suited for penetrative as opposed to superficial surgery. Solar photons are also viable candidates for such radiative surgery, provided they can be concentrated to the flux levels of surgical lasers, coupled into an optical fibre and efficiently delivered to a remote operating theatre. The simplicity and the potentially low cost of a solar surgery unit counterbalance its feasibility being restricted to mid-day hours in sunny regions.

Feuermann and Gordon (2001) [21] developed and analysed gradient-index rod lenses as imaging optical elements, but their capability as flux concentrators has not been explored. Both analytic methods and computer raytrace simulations were used for a comprehensive evaluation of the concentration and efficiency of these rods. It predicted that they could be well suited as

concentrators for the distal end of laser fibre optic surgical units, toward improving surgical efficacy and reducing expensive laser power.

Gordon et al. [22–24] reported the experimental realization and field experience of a recently proposed solar fibre-optic mini-dish concentrator. The prototype is 200 mm in diameter. It was put forward that they had repeatable transported concentrated sunlight in a 1-mm-diameter optical fibre and measured flux levels of 11–12 kilo suns at a remote target (up to 20 m away). The prototype—assembled from off-the-shelf parts and customized items that rely solely upon existing commercial technologies—proved impervious to dust penetration and condensation. For the particular application of solar surgery, dielectric second-stage concentrators were designed and fibre tips were sculpted to boost flux concentration by a factor of 2 to 4, for light extraction into air and tissue, respectively. The findings strengthen the feasibility of the efficient and complete de-coupling of the collection and of the remote delivery of highly concentrated solar radiation. It was indicated that surgical tissue transformations normally produced with lasers were demonstrated experimentally with highly concentrated sunlight. Experimental results were presented to substantiate that highly concentrated sunlight can pragmatically produce the same extent, rate and type of photo thermal tissue damage ordinarily generated with laser fibre-optic surgery. The experimental results demonstrated that solar surgery can produce lesions up to several cm^3 in volume, with a surgical efficacy as good as that of lasers for corresponding procedures. It was emphasized that solar surgery could offer an inexpensive alternative to surgical lasers, albeit with limitations on feasible locations and operating periods [22–24].

2.4. *Photo-bio reactors, hydrogen generation and photochemical reactions*

Photobioreactor designs are commonly restricted by the ability of conventional optical systems to deliver prescribed solar intensities and flux distributions at high collection efficiency. Marinangeli and Ollis [25] extended the concept of using optical fibres to distribute light within heterogeneous photo-assisted catalysts to photo-electrochemical cells. The potential drop in a semiconductor photoelectrode was predicted for various types of ohmic electrical contacts, and the optimum contact location is determined. The variation of electrical conductivity with temperature in non-isothermal bundles of semiconductor-coated optical fibres was considered [25].

St. George and Feddes (1991)[26] developed and evaluated a prototype light collection and transmission device for the potential of irradiating plants grown in an opaque growth chamber. Results indicated that the device transmitted light with a photon flux of 130 1amol/s/m^2 (4000–7000 nm) to the bottom of the growth chamber when direct solar radiation was 800 W/m^2 (300–2500 nm) outside.

Jaramillo et al. [27] presented an alternative way to transmit concentrated solar energy, which may be applied in hydrogen production by photoelectrolysis. They suggested that it is possible to obtain high efficiency in the photoelectrochemical conversion systems with a simple structural design. The basic idea proposed is to place an optical fibre in a paraboloidal mirror receptor plane. The appropriate conditions existing between a paraboloidal mirror reflective surface, Ag or Al, and an optical fibre (low doping, commercial type) was studied. The theoretical efficiency of the conversion system was obtained and analysed [27].

Exploitation of photosynthetic cells for the production of useful metabolites requires efficient photobioreactors. Many laboratory-scale photobioreactors have been reported but most of them are extremely difficult to scale up. Furthermore, the use of open ponds and outdoor tubular photobioreactors is limited by the requirement for large spaces and the difficulty in maintaining sterile conditions. In view of this, Ogbonna et al. [28] have designed and constructed an internally illuminated stirred tank photobioreactor. The photobioreactor is simple, heat sterlizable and mechanically agitated like the conventional stirred tank bioreactors. Furthermore, it can be easily scaled up while maintaining the light supply coefficient and thus the productivity constant. A device was installed for collecting solar light and distributing it inside the reactor through optical fibres. It was equipped with a light tracking sensor so that the lenses rotate with the position of the sun. This makes it possible to use solar light for photosynthetic cell cultivation in indoor photobioreactors. As a solution to the problems of night biomass loss and low productivity on cloudy days, an artificial light source was coupled with the solar light-collecting device. A light-intensity sensor monitors the solar light intensity and the artificial light is automatically switched on or off, depending on the solar light intensity. In this way, continuous light supply to the reactor can be achieved by using solar light during sunny periods and artificial light at night and on cloudy days [28].

Kim and An [29] applied the optical-fibre photobioreactor with an internal illumination system to increase the light availability. Sunlight was used as the main light energy during daytime and a metal-halide lamp was applied as an additional light energy at night. Most UV light was eliminated by the chromatic aberration of the aspherical lenses in the solar light collector and 60% of infrared light intensity was eliminated [29].

Gordon [30] explored how non-imaging optical designs can be tailored to reactor conditions that maximize bio productivity. Two distinct classes of photobioreactors were considered: (1) stationary outdoor units and (2) an indoor reactor that requires the total separation of the collection and delivery of solar radiation. For practical and economic reasons, the latter obliges solar collectors of immense optical concentrations. It was indicated that the outdoor direct-illumination units comprise stationary mirrored troughs placed around standard reactor shapes, and

replace expensive reactors with inexpensive reflectors, while enhancing bio productivity. For the indoor reactors, dual-axis tracking solar fibre-optic mini-dish concentrators were adopted to collect, concentrate and transport sunlight to a remote reactor. In all cases, the principal demands were listed as (a) accommodating reactor shapes with high ratios of irradiated surface area to volume; (b) uniform flux on the irradiated surfaces; (c) high efficiency for collecting and delivering solar radiation; (d) being based on existing and affordable technologies; and (e) compactness. Flux levels of $2000\,mol/m^2/s^1$ of photosynthetically active radiation were realistically attainable over the entire transparent surface of the reactor [30].

Joo et al. [31] considered plastic optical fibres (POFs) as light-transmitting media and substrates for the potential use in photocatalytic environmental purification system, and the performance of POFs was also compared with that of quartz optical fibres (QOFs). After the characteristic of POFs in terms of light transmittance was determined in the beginning, detailed investigation was further conducted through the photocatalytic degradation of trichloroethylene. It was concluded that the use of POFs is preferred to QOFs since the advantages such as ease of handling, lower cost and relatively reasonable light attenuation at the wavelength of near 400 nm can be obtained [31].

Gordon et al. [32] described approaches that offer a potentially far less-expensive production facility that is also amenable to being scaled up, in contrast to the conventional costly technologies of laser ablation furnaces and plasma discharge chambers, which employ new strategies for the efficient use of concentrated sunlight to synthesize carbon nanomaterials. The designs employed solar fibre-optic mini-concentrators that completely decouple the collection and remote indoor delivery of solar radiation into a high-temperature nanomaterial reactor. High flux on the target graphite rod was produced by the overlap of low numerical aperture concentrator units—a strategy that also accommodates the sizable gap required between the target inside the reactor and the distal fibre tips on the reactor exterior. It was found that this in turn allows a dramatic reduction in solar input relative to earlier solar nanomaterial furnaces. Designs and performance estimates for a system with target temperatures in excess of 3000 K and hence with significant nanomaterial yields were provided [32].

The strategy of exploiting photosynthesizing microalgal cultures to remove carbon dioxide (CO_2) from flue gases through fixation has the potential to effectively diminish the release of CO_2 to the atmosphere, thus helping to alleviate the trend toward global warming. Ono and Cuello [33] indicated that the use of fibre optic-based solar concentrating systems for micro algal photobiorectors has the potential to meet the two essential criteria in the design of a lighting system for algal photobioreactors: (1) electrical energy efficiency and (2) lighting distribution efficiency. The overall efficiencies of solar-concentrating systems have significantly improved in recent years, exceeding 45%. Meanwhile, achieving uniform lighting distribution within photobioreactors constitutes probably the greatest challenge in using fibre optic-based solar concentrators as a lighting system for photobioreactors. It was stressed that the light-emitting fibres appeared to be a most promising candidate in achieving such uniform light distribution in photobioreactors [33].

2.5. Solar power generation

Jaramillo et al. [34] developed a theoretical thermal study of optical fibres transmitting concentrated solar energy. An energy equation for simultaneous conduction and radiation of heat through optical fibres was obtained. To transmit concentrated solar energy, an optical fibre tip was placed in the focus of a small paraboloidal mirror. The role of aluminium and silver was studied as the reflective surface on the mirror that allows one to concentrate the solar energy. The power supply was estimated to be 26 W at the end of a 10 m-long fibre with 88% transmission efficiency. It was indicated that the thermal study considers a wavelength-dependent absorption coefficient of the optical fibre core in order to obtain the radiative heat flux in the fibre. The time evolution of the temperature distribution was obtained by a finite-difference method. It was predicted that the fibre can be used for 6 h [34].

Kribus et al. (1999) offered an approach that minimizes the length of fibres while fully utilizing the flexibility advantage. It was underlined that the use of fibres in concentrating solar thermal systems has potential advantages of providing unprecedented flexibility in the final concentration and the receiver design. A central receiver system based on the tower reflector with optical fibres (TROF) was presented as a case study in a comparison between conventional concepts of solar thermal power generation and new concepts employing optical fibres. Two new approaches to thermal conversion, utilizing the flexibility of a fibre-based system, non-isothermal high-temperature receivers and distributed receivers, were investigated. An approximate performance and cost analysis that assumes mass-produced solar-optimized fibres was presented. The effects of system size and several fibre types were discussed. It was seen that the use of current optical fibres may become competitive for solar-driven electricity-generation systems under optimistic assumptions. The analysis points to research and development directions that could lead to cost-effective TROF and other optical fibre-based systems in the future [35]. In the latter study, Kribus et al. [36] presented a study of the potential use of optical fibres for solar thermal power generation. The main performance characteristics (numerical aperture and attenuation) and typical costs of currently available fibres were discussed. Several approaches to the application of fibres were presented, for centralized (tower, central receiver) and distributed (dish-engine) systems. The overall system design-point efficiency and overall system cost were estimated. A scaling relation between system size and the

cost of the fibre component was identified, which severely limits the applicability of fibres to small systems only. It was found that the overall system cost for centralized systems is higher than the currently competitive range, even under optimistic assumptions of mass production of major components. It was noted that a significant reduction in fibre cost is required before the use of fibres for centralized solar power generation can become competitive. However, it was shown that the use of fibres can achieve competitive performance and costs, comparable to the costs of conventional dish systems in distributed generation using dish/engine systems [36].

Kaushika and Reddy [37] presented the design, development and performance characteristics of a low-cost solar steam-generating system, which incorporates recent design and materials innovations of parabolic dish technology. The concentrator investigated was a deep dish of rather imperfect optics, made of silvered polymer reflectors fitted in the aluminium frame of a satellite communication dish. It was indicated from preliminary field measurements and cost as well as from performance analyses of the system [37] that a solar to steam conversion efficiency is 70–80% at 450 °C and a collector system cost is \$200–225/m^2.

Gordon and Choon [38] pointed that there is a performance leap, relative to current state-of-the-art solar cooling systems, stems from the introduction of solar fibre-optic mini-dish systems and it could deliver high-temperature heat at high solar to thermal conversion efficiencies. It was analysed that a further boost in net COP to around 1.4 can be achieved by modifying the conventional scheme to a thermodynamic cascade that takes maximal advantage of high-temperature input heat by solar mini-dish systems. It was also mentioned that the energy of concentrated sunlight can be stored compactly as ice produced at a retrofitted evaporator of the mechanical chiller. The compactness and modularity of solar mini-dish systems were indicated as its advantages indicated the possibility for small-scale ultra-high-performance solar cooling systems [38].

Feuermann and Gordon [21] proposed a new approach for concentrating photovoltaic systems that could easily attain the maximum flux levels commensurate with solar cell technology. The collection unit offered was a miniature paraboloidal dish (e.g., with a diameter of the order of 10 cm) that concentrates sunlight into a short glass rod. The flux distribution of the transported light was homogenized in a miniature glass kaleidoscope that is optically coupled to a small, high-efficiency solar cell. It was emphasized that collection units could be assembled into modules and arrays that produce almost any prescribed power level and all system elements were predicated on existing technologies [39].

Jaramillo et al. [40] carried out a theoretical and experimental thermal behaviour study of optical fibres with a high-purity SiO_2 core transporting concentrated radiative energy. A theoretical unidimensional model for the simultaneous transport of heat by conduction and radiation in optical fibres, including the heat losses by convection at the surface, was developed. This model considers a constant linear absorption coefficient and it was solved analytically. An experimental method to determine the linear coefficient of absorption was developed. The time evolution of the axial temperature distribution of two kinds of fibres was recorded and compared with the theoretical predictions. Theoretical model proposed was validated by these experimental results [40].

Jaramillo and Rio [41] presented a thermodynamic optimization of a solar mini-dish/stirling system. It was noted that the solar collector heat losses by convection and radiation are diminished by using optical fibres to transport concentrated solar energy. An absorber-heater for the solar heat engine was analysed by using the first law and the second law to ensure the reduction of the heat losses. Taking into account internal and external irreversibilities for the solar heat engine, the optimal operating temperature and the overall efficiency of the system were established [41].

2.6. *Solar-pumped lasers*

Solar-pumped lasers can be used for space and terrestrial applications. Solar pumped solid-state lasers may be used on earth for laser photochemistry [42] and in space for wireless power transmission [43], satellite to satellite optical communication [44] and remote sensing. Being the main energy source in space, solar energy may pump solid-state lasers directly or indirectly. In direct pumping, solar cells are used for solar to electric energy conversion, diode lasers convert the electric power to the pumping light. Lando et al. [45] claimed that direct solid-state laser pumping with solar light is inherently more efficient, simpler and more reliable [45].

Flexible optical fibres and fibre bundles can be used to transfer concentrated sunlight to a desirable place where it could be used to pump a solid-state laser. Liang et al. [46] used an optical fibre bundle with a frustum-type output end to transmit and concentrate solar energy to a flux level that was high enough to pump a solid-state laser with the aim of CW pumping a laser crystal outside the focusing area of a primary parabolic mirror. The transmission properties of a fibre optic frustum-type concentrator was first analysed with the help of a ray-tracing programme, which revealed strong influences of both output diameter and length on the transmission efficiency of a frustum concentrator. In the study, the idea of achieving an ideal angular transformer with fibre optic technology in the area of nonimaging optics was also proposed. The output section of each optical fibre was polished to form a hexagonal frustum. When seven of these polished frusta from the optical fibres were joined together, a novel solar energy concentrator was obtained. The output power from the concentrator end was 67 W, corresponding to the solar flux of 23 W/mm^2. It was reported that the maximum solar flux of 28 W/mm^2

was obtained with a single optical fibre of conical output end [46].

Pires et al. [47] noted a flexible bundle consisting of seven optical fibres polished to a hexagonal form was placed at the focus of a primary parabolic mirror to capture the solar energy in the core region of the focal spot. The radiation exiting the fibres was concentrated with a compound parabolic collector (CPC) or with a long conical concentrator. A moderate optical flux of $13\,W/mm^2$ was measured, with a large angular divergence as expected together with a non-homogeneous light distribution from the output end of the CPC concentrator; both were certainly responsible for the unsuccessful attempts at pumping the laser. Hence, a long conical concentrator was designed and built. Experimental results showed that both the incident ray acceptance capability and the output light quality are better than the CPC. A solar flux of about $20\,W/mm^2$ was obtained [47].

Lando et al. [48] reported on solar side-pumped Nd:YAG laser experiments, which included comprehensive beam quality measurements and demonstrated record collection efficiency and day-long operation. A $6.75\,m^2$ segmented primary mirror was mounted on a commercial two-axis positioner and focused the solar radiation towards a stationary non-imaging-optics secondary concentrator, which illuminated an Nd:YAG laser rod. Solar side-pumped laser experiments were conducted in both the low and the high pumping density regimes. The current results were compared to previous solar side-pumped laser experiments, including experiments at higher pumping density but with low collection efficiency. Scaled-up design was presented for a 400 W laser pumped by a solar collection area of $60\,m^2$, incorporating simultaneously high collection efficiency and high pumping density [48].

In this section, the studies based on the idea of TCSEvOF are summarized briefly. A detailed review of studies conducted on TCSEvOF systems is given in Table 1.

A low-cost, high reflective, tracking the Sun along two axes offset paraboloidal dish integrated FOB established in Ege University Solar Energy Institute (EU-SEI) is offered in the present study. Although the main aim of the system is solar lighting to non-daylit areas, it can be possible to transform by additional components and some modifications for the other objectives. At this point, it can be more explicative to mention the distinctive sides of the system proposed. The originalities and contributions of the system proposed are (i) being processed by chrome, (ii) having the offset shape, (iii) having a very affordable tracking system and (iv) taking into account the dispersion angle to determine the image size on the focal point. These subjects are explained clearly as below.

High reflective paraboloidal dishes previously referred to in the literature are covered by aluminium or silver. It can be made of glass mirrors. The paraboloidal mirrors made of glass can result in very high mechanical loads. Also, practically it may be difficult to protect and utilize the glass mirror paraboloidal dish. In the present study, the offset paraboloidal dish was adopted from a simple existing satellite antenna and processed by chrome for providing high reflectivity. Thus, the cost of the dish was diminished significantly.

Another feature of the system offered is that the shape of the dish is offset. Replacing the offset antennas to symmetrical ones in daily life has inspired this study. It is known that offset antennas have bigger collection efficiency than symmetrical ones for the same aperture areas. Offset dishes do not include shading area on the concentrator surface due to its receiver on the focal point. It is the most important feature for more effective concentration, especially for solar energy application. The receiver on the focal point placing out of the aperture area can be controlled easily for offset paraboloidal dish. FOB integrated the concentrating unit is exposed to bending effects resulting in larger loss with the sun tracking system. Since the receiver on the focal point is placed out of the aperture area, there are no shading effects on the dish surface due to the receiver and FOB.

A new sun tracking system consisting of affordable materials and an electronic board has been utilized by the TCSEvOF system established in EU-SEI. Sun tracking was supplied by an electronic board system integrated with four sensors along dual axes and two motors. Two of the sensors perceive the light horizontal axis and the others do the same job vertically. The sensors consist of light-dependent resistance (LDR). LDRs show less resistance under bright light, and it has larger resistance in dark environment, that is there is an inverse proportion between the light and resistance. It was decided that it should not be appropriate to give the electronic circuit scheme due to keeping tests of the tracking system and being out of the scope. Results on the precision of this sun tracking system will be presented in further studies. Theoretical analyses carried out in this study assumed that the tracking error can be accepted as zero. The capital cost of the tracking system including electronic board, sensors, cables and motors is about $178.

Some mathematical modelling assuming perfect and specular reflectance and zero dispersion angle can be found in the literature [34,41]. However, it can be exposed to considerable dispersion effects in applications. Therefore, it is very crucial to determine the dispersion angle to size of the receiver. In this study, the dispersion angle to optimize receiver size as well as the solar half–angle were considered.

3. Mathematical modelling

In this section, the mathematical model for coupling of the FOB and a low-cost offset paraboloidal dish were studied. The optimal geometrical parameters to couple offset paraboloidal dish and FOB were analysed.

The effective irradiance incoming to aperture plane is the beam irradiance, except for the low concentrating collectors. An incident beam of solar radiation is a cone with an

Table 1
Studies on TCSEvOF systems

Groups of studies	No.	Year	Author(s)	Location	Concentrator type	Fibre length (m)	Efficiency (%)		Type of study	
							Optical	Total	Theoretical	Experimental
Characterization of the system	1	1982	Cariou et al. [5]	France	Paraboloidal dish	10	70	X	✓	✓
	2	1985	Dugas et al. [6]	France	Paraboloidal dish	N/A	N/A	X	✓	✓
	3	1993	Khatri et al. .[7]	Cincinnati, USA	CPC	N/A	X	X	✓	X
	4	1998	Liang et al. [3]	Portugal	Telescope mirror	3 (Bundle)	60	X	X	✓
	5	1999, 2002	Gordon et al. [8,9]	Israel	Paraboloidal dish	20	80	X	✓	✓
	6	2000	Jaramillo et al. [10]	Mexico	N/A	X	X	X	✓	X
	7	2003	Johnston et al. [11]	Australia	Paraboloidal dish	X	90	X	X	✓
	8	2005	Nagai [12]	Japan	Paraboloidal dish	X	X	X	✓	X
	9	2006	Luca [13]	Italy	N/A	X	X	X	✓	X
	10	2006	Liu et al. [14]	China	Paraboloidal dish	X	X	X	✓	X
Solar lighting	1	2003	Ciamberlini et al. [15]	Italy	Spherical and aspherical mirrors	10	N/A	68–72	✓	✓
	2	2003, 2004, 2005	Schlegel, Burkholder and Cheadle [16–19]	Madison, USA	Paraboloidal dish	N/A	N/A	N/A	✓	✓
	3	2005	Tsangrassoulis et al. [20]	Greece	Fresnel based (diameter 1 m)	N/A	N/A	N/A	X	✓
Solar surgery	1	2001	Feuermann and Gordon [21]	Israel	Paraboloidal dish	X	X	X	✓	X
	2	2002, 2003	Gordon et al. [22–24]	Israel	Paraboloidal dish	20	N/A	N/A		✓
Photo-bio reactors, hydrogen generation and photochemical reactions	1	1982	Marinangeli and Ollis [25]	Princeton, USA	N/A	N/A	N/A	N/A	✓	X
	2	1991	St. George and Feddes [26]	Canada	N/A	N/A	N/A	N/A	X	✓
	3	1998	Jaramillo et al. [27]	Mexico	Paraboloidal dish	10	88.95	63	✓	X
	4	1999	Ogbonna et al. [28]	Japan	Fresnel based	N/A	N/A	38	X	✓
	5	2000	Kim and An [29]	South Korea	Fresnel based	N/A	N/A	N/A	X	✓
	6	2002	Gordon [30]	Israel	Non-imaging (e.g. Trough) and paraboloidal dish	N/A	N/A	N/A	✓	X
	7	2003	Joo et al. [31]	South Korea	X	X	X	X	X	✓
	8	2004	Gordon et al. [32]	Israel	Paraboloidal dish	X	X	X	✓	
	9	2004	Ono and Cuello [33]	Arizona, USA	Fresnel based, mirror (double) based with silica cables, mirror (single) based with liquid-based cables	10	X	23.2, 40.5, 46.1 (respectively)	✓	X
Solar power generation	1	1999	Jaramillo et al. [34]	Mexico	Paraboloidal dish	10	88	X	✓	X
	2	1999, 2000	Kribus et al. [35,36]	Israel	Tower and hyperboloidal reflector and paraboloidal dish	N/A	68–89	16–25	✓	X

Table 1 (*continued*)

Groups of studies	No.	Year	Author(s)	Location	Concentrator type	Fibre length (m)	Efficiency (%)		Type of study	
							Optical	Total	Theoretical	Experimental
	3	2000	Kaushika and Reddy [37]	India	Paraboloidal dish	X	70–80	N/A	✓	✓
	4	2000	Gordon and Choon [38]	Israel	Paraboloidal dish	X	90	23	✓	X
	5	2001	Feuermann and Gordon [39]	Israel	Paraboloidal dish	N/A	85	20	✓	X
	6	2002	Jaramillo et al. [40]	Mexico	Lens system	0.094–1.578	X	X	✓	✓
	7	2002	Jaramillo and Rio [41]	Mexico	Paraboloidal dish	3	85.7	46	✓	X
Solar-pumped lasers	1	1999	Lando et al. [45]	Israel	Heliostat and CPC	X	N/A	N/A	X	✓
	2	1999	Liang et al. [46]	Portugal	Double CPC and conical concentrator	N/A	N/A	N/A	X	✓
	3	1999	Pires et al. [47]	Portugal	Frustum type	N/A	N/A	N/A	X	✓
	4	2003	Lando et al. [48]	Israel	Segmented mirror and CPC	X	N/A	10–25	X	✓

angular width of 0.53° [49]. The characteristics of the image to analyse the concentrated energy require to be put forward. The width of the solar images in the focal plane increases by the rim angle. The focal length is a determining factor in image size, and the aperture is the determining factor in total energy. It is assumed that the beam radiation is normal to the aperture and the reflection is specular and perfect.

Each optical fibre has a pure transparent inner core and a thin transparent outer cladding. The total internal reflection allows us to guide the sunlight through the fibre. The fibre core has an index of refraction n_1, which is greater than that of the cladding n_2. The ratio of the core index and cladding index determines the acceptance/admission angle of radiation $\theta_{\max}$ at which total internal reflection occurs:

$$\mathrm{NA} = \sin\,\theta_{max} = (n_1^2 - n_2^2)^{1/2}, \tag{1}$$

where NA is the numerical aperture that is a measure of the admission angle $\theta_{\max}$ of the fibre-optic bundle.

On the other hand, the energy rate $\dot{Q}_{\mathrm{p}}$ hitting a flat receiver of a paraboloidal concentrator, where the optical fibre bundle inlet is placed, is given by

$$\dot{Q}_{\mathrm{p}} = \pi f^2(\sin^2\phi_{\mathrm{r}} - \sin^2\phi_{\mathrm{s}})\rho_{\mathrm{m}} G_{\mathrm{b}}, \tag{2}$$

where f is the focal length, ρ_{m} is the reflectance of the surface, ϕ_{r} is the rim angle of the paraboloidal dish, ϕ_{s} is the shading angle because of the receptor size and G_{b} is the solar beam irradiance [34,41]. It is important to mention that the rim angle ϕ_{r} should be equal to or smaller than the optical fibre admission angle. In optimum conditions, to ensure that the whole radiation gets in the fibre bundle, the maximum rim angle of the paraboloidal dish must be

$$\phi_{\mathrm{r}} = \theta_{max} \tag{3}$$

that corresponds to the maximum admission angle of the optical fibre. The focal length f and the aperture diameter D_{a} for the paraboloidal dish are related by

$$\frac{f}{D_{\mathrm{a}}} = \frac{1}{4\,\tan(\phi_{\mathrm{r}}/2)} \tag{4}$$

and for a flat receiver (at the focal plane of a paraboloidal concentrator) the receptor diameter D_{r} is given by

$$D_{\mathrm{r}} = \frac{D_{\mathrm{a}}\,\sin(0.267^\circ + \delta/2)}{\sin\,\phi_{\mathrm{r}}\,\cos(\phi_{\mathrm{r}} + 0.267^\circ + \delta/2)}, \tag{5}$$

where $\delta/2$ is dispersion angle as a measure of the angular errors of the reflector surface and 0.267° is the half-angle of the incident beam cone of the solar radiation. It is important to indicate that the receptor diameter D_{r} should be equal to the diameter D_{of} at the input section of the fibre-optic bundle:

$$D_{\mathrm{of}} = D_{\mathrm{r}}. \tag{6}$$

Taking into account Eqs. (4) and (5), we can write the optimal focal length f_{o} as

$$f_{\mathrm{o}} = \left(\frac{D_{\mathrm{of}}}{4\,\tan(\theta_{max}/2)}\right)\left(\frac{\sin\,\theta_{max}\,\cos(\theta_{max} + 0.267^\circ + \delta/2)}{\sin(0.267^\circ + \delta/2)}\right). \tag{7}$$

The energy rate at the inlet of the optical fibre bundle $\dot{Q}_{\mathrm{i,of}}$ can be written as

$$\dot{Q}_{\mathrm{i,of}} = A_{\mathrm{of}}\rho_{\mathrm{m}} G_{\mathrm{b}} F_{\mathrm{s}} C_{max}, \tag{8}$$

$$F_{\mathrm{s}} = \frac{\sin^2\theta_{max} - \sin^2\phi_{\mathrm{s}}}{4\tan^2(\theta_{max}/2)}, \tag{9}$$

$$C_{max} = \frac{A_a}{A_{of}} = \frac{\sin^2\theta_{max}\cos^2(\theta_{max} + 0.267^\circ + \delta/2)}{\sin^2(0.267^\circ + \delta/2)}, \tag{10}$$

where A_{of} is the area of the input fibre-optic bundle, A_a is the aperture area of the paraboloidal mirror, C_{max} is the maximum ratio of geometrical concentration and F_s is the view factor for a flat receiver of paraboloidal mirror and both depend on θ_{max}.

A radiative flux $Q_{i,of}$ as high as possible can be obtained by the maximum value for θ_{max} from the view factor F_s and the maximum geometrical concentration C_{max}:

$$F_s C_{max} = g(\theta_{max}) = \left(\frac{\sin^2\theta_{max}}{4\tan^2(\theta_{max}/2)}\right) \times \left(\frac{\sin^2\theta_{max}\cos^2(\theta_{max}+0.267^\circ)}{\sin^2(0.267^\circ)}\right). \tag{11}$$

At this point, we consider a perfect/ideal paraboloidal mirror with zero dispersion ($\delta/2 = 0$) and for the shading angle

$$\phi_s = 0. \tag{12}$$

To determine the maximum value for the admission angle θ_{max} of the optical fibre and to obtain the maximum energy rate at the inlet of the optical fibre bundle, it can be set as

$$\frac{dg(\theta_{max})}{d\theta_{max}} = 0, \quad 0 \leqslant \theta_{max} \leqslant 90, \tag{13}$$

$$\theta_{max,max} \cong 40^\circ, \tag{14}$$

$$g_{max}(40^\circ) \cong 8640. \tag{15}$$

It is important to note that if D_{of} and θ_{max} for the optical fibre bundle are previously defined, then the aperture diameter D_a and the rim angle ϕ_r for the paraboloidal mirror are fixed.

On the other hand, from the definition of decibel losses per unit length, η_{FOB} optical efficiency of fibre-optic bundle and the energy rate $\dot{Q}_{o,of}$ at the end of the optical fibres can be expressed as

$$\eta_{FOB} = \frac{\dot{Q}_{o,of}}{\dot{Q}_{i,of}} = 10^{-L\,dB_{loss}/10}, \tag{16}$$

where L is the fibre-optic bundle length and dB_{loss} is the optical fibres attenuation.

Taking into account the results from equations, the optical efficiency of the collector system for the optimum value can be given as

$$\eta_{o,opt} = \rho_m 10^{-L dB_{loss}/10} F_s(\theta_{max,max}). \tag{17}$$

where F_s is the view factor

Overall system efficiency can be expressed as

$$\eta_s = \frac{\dot{Q}_{o,of}}{A_a G_b}. \tag{18}$$

Maximum and minimum size of the image on the focal point given firstly by Gordon et al. [22] was reconstructed by modifying the equations with dispersion angle.

The diameter d_{min} of the approximately uniform-flux core region of the focal spot is

$$d_{min} = 2D_a[1/4\ \tan(\phi_r/2)]\sin(0.267^\circ + \delta/2). \tag{19}$$

The focal spot diameter d_{max} that accepts essentially all reflected rays is

$$d_{max} = \frac{D_a[1 + (1/\tan^2(\phi_r/2))]^2 \sin(0.267^\circ + \delta/2)}{2[(1/\tan^2(\phi_r/2)) - 1](1/\tan(\phi_r/2))}. \tag{20}$$

When designing for maximum flux concentration from the dish, the diameter of FOB should be selected as d_{min}; for a while maximum efficiency designs the diameter of FOB will be closer to d_{max}. The optical fibres having large numerical aperture, large core diameter and less attenuation should be used for effective TCSEvOF systems.

3.1. The system proposed

Fig. 1 defines the cross-section of the low-cost offset paraboloidal dish proposed in the present study schematically. The drawing, especially FOB on the focal point, has been exaggerated to be understood clearly. An offset paraboloidal dish is a part of the full symmetrical one. This missing part of the dish can be defined by using the angle of α. The part corresponding to the angle of ϕ_r–α does not exist for offset paraboloidal dishes. The shading angle for the offset paraboloidal dish is zero. However, it was calculated that the shading angle for the symmetrical one is 1.1° to analyse obtainable output power.

The energy rate on the focal plane for offset dish can be described by modifying Eq. (2) and taking into account the lacking part corresponded ϕ_r–α as below

$$\dot{Q}_p = \pi f^2[\sin^2\phi_r - \sin^2(\phi_r - \alpha)]\rho_m G_b. \tag{21}$$

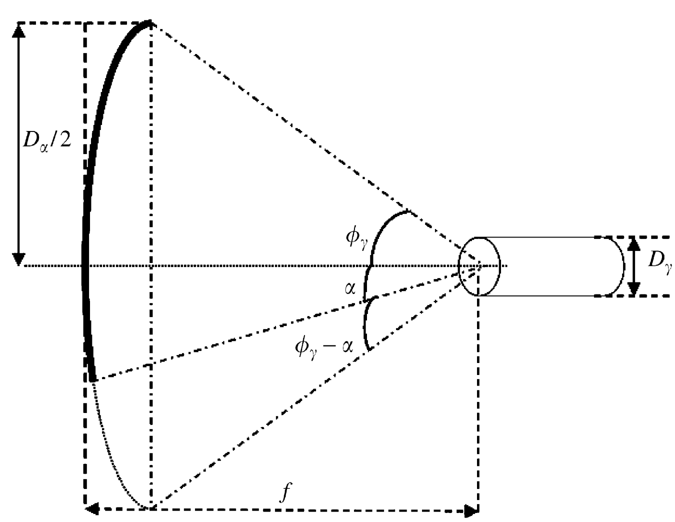


Fig. 1. The cross-section of the low-cost offset paraboloidal dish proposed.

Table 2
Parameters of the low cost offset paraboloidal dish

Parameters	
D_a (m)	1.04
D_r (m)	0.03
f (m)	0.78
f_o (m)	0.87
ϕ_r (°)	36.87
ϕ_s (°)	0
θ_{max} (°)	30.69
$\delta/2$	0.39
α (°)	28
dB_{loss} (dB/km)	200
L (m)	3.12
C_{max}	1730.84
NA	0.51
$g_{(max)}$	7628.92
d_{min} (m)	0.0178
d_{max} (m)	0.0248
ρ_m	0.85
η_{FOB} (%)	87
η_o (%)	63
η_s (%)	59

Table 2 presents measured and calculated parameters of the low-cost offset paraboloidal dish.

FOB used in the present study carried out in EU-SEI has been composed of large core flexible optical fibres. The length of FOB is 3.12 m and the diameter is 0.03 m. The maximum admission angle of FOB was determined by Eq. (1). Rim angle of the dish was calculated by Eq. (4). The attenuation of the optical fibre is indicated as 200 dB/km by the manufacturer data. Transmission efficiency of FOB was found to be 87% by neglecting internal and external losses of optical fibres. For maximum concentration ratio, the rim angle was used in Eq. (10) and was found to be 1731.

In the case of substituting the rim angle to maximum acceptance angle, view factor F_s was calculated as 0.81, and using θ_{max} in Eq. (9) F_s was found to be 0.86. Consequently, optical efficiency of the whole system was calculated as 68% in optimum condition, while it was 63% for the system proposed. It can be seen this result is very close to the optimum value. Overall system efficiency was found to be 59% according to Eq. (18).

The other significant parameter is the dispersion angle. The size of the image on a focal point will be larger than the theoretically calculated one because of surface imperfections. Even the condition of the ideal reflection, high uniform flux at the centre and elliptical flux distribution surrounding it will be observed due to the solar half-angle. Therefore, the effects of the dispersion and scattering should be taken into account to size and optimize the systems correctly. It is important to increase the efficiency and reduce the capital cost of the system. Since the bigger part of the cost of TCSEvOF systems consists of optical fibres and the price of the large core optical fibres is still high for low-cost solar applications. The most crucial reason of the optimization is to decrease the number of the optical fibres used for the bundle.



Fig. 2. The TCSEvOF system established in EU-SEI.

The size of the image has uniform flux as given by d_{min}. As indicated in Table 2, d_{min} was calculated as 1.78 cm according to Eq. (19). If the aim is to receive all flux concentrated on the focal point, it should be considered maximum image size. For the existing system, d_{max} was calculated as 2.48 cm by considering dispersion effects according to the Eq. (20). However, the diameter of FOB for the TCSEvOF system proposed was chosen as a bundle of 3.0 cm by taking into consideration the errors to be resulted by the sun tracking in this study.

Fig. 2 represents the TCSEvOF system established in EU-SEI. It has been installed on the roof of a test space,which was placed in the campus of EU-SEI. This system includes offset paraboloidal dish, sun tracking system with dual axis and FOB on the focal point. The main aim of the system is solar lighting to non-daylit indoor of the test space.

The FOB of TCSEvOF system set up in EU-SEI is seen from Fig. 3. It can be considered that the FOB is a concentrated solar energy transportation pipe. It is a critical factor to be bundle of the optical fibres in a way of well-arranged, especially at the entrance and end to success total internal reflection. Practically, it is not possible to eliminate the holes between the optical fibres, but it can be

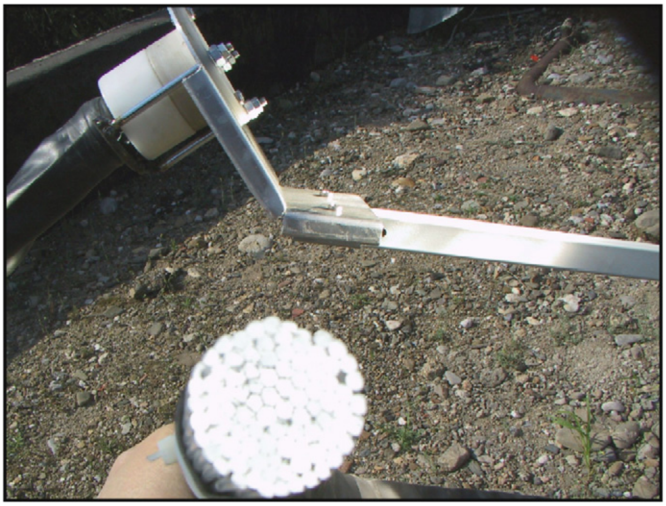


Fig. 3. The FOB of TCSEvOF system established in EU-SEI.

minimized. Here we have utilized the optical fibres having different core diameters to achieve this aim. It is very important that the bundling process should be done by qualified technicians.

4. Results and discussion

Izmir, the third big city of Turkey, is located at a latitude of 38.46°N, longitude of 27.22°E and altitude of 27 m. Izmir being in the Mediterranean climate belt has hot and dry summers, and cool and rainy winters. Hourly global irradiance data of 2004 obtained EU-SEI meteorology station were used to put forward the hourly normal beam radiation reaching the aperture plane of the paraboloidal dish. Global irradiance data were separated to beam and diffuse component by using the Hottel Clear Sky Model [49]. The normal beam radiation calculated hourly was used to

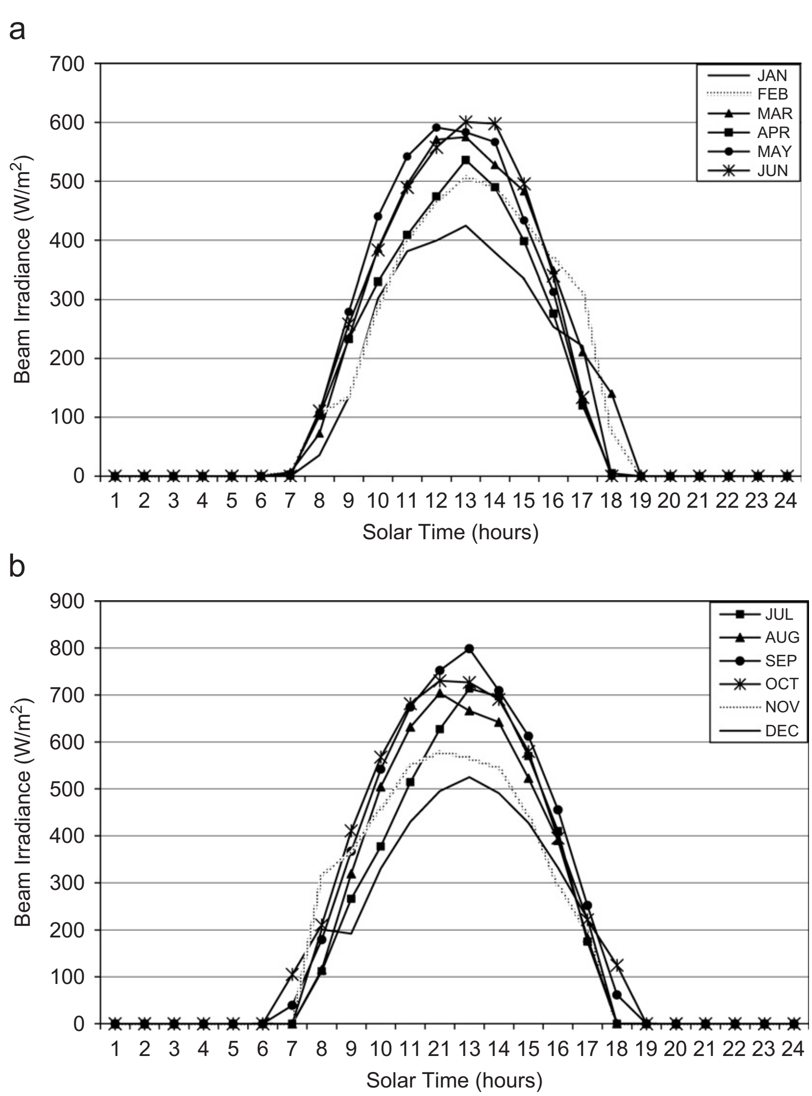


Fig. 4. Monthly average hourly solar beam irradiance (W/m^2): (a) from January to June and (b) from July to December.

evaluate the monthly average hourly output power obtained from the symmetrical and offset paraboloidal dishes.

Figs. 4a and b show monthly average hourly normal solar beam irradiance (W/m^2) with sun tracking along two axes for Izmir. It can be seen that the solar normal beam irradiance values exceed 600 W/m^2 except for November, December and January for Izmir. For January, solar normal beam irradiance values exceed 400, and 500 W/m^2 for November and December. These data were presented to estimate the output power of the system.

Figs. 5a and b present monthly average hourly output power for the offset paraboloidal dish proposed. It can be understood from the graph that the output power can reach 250 W in solar noon for January, and it varies between 250 and 350 W for February, March, April, May and June. Similarly, the output power can reach 300 W in solar noon for December; it has values ranging from 300 to 450 for July, August, October, November, and it exceeds 450 for September.

Figs. 6a and b define monthly average hourly output power for a symmetrical paraboloidal dish. It can be understood from the graph that the output power has the values between 200 and 250 W in solar noon for January, and it varies between 250 and 350 W for February, March,

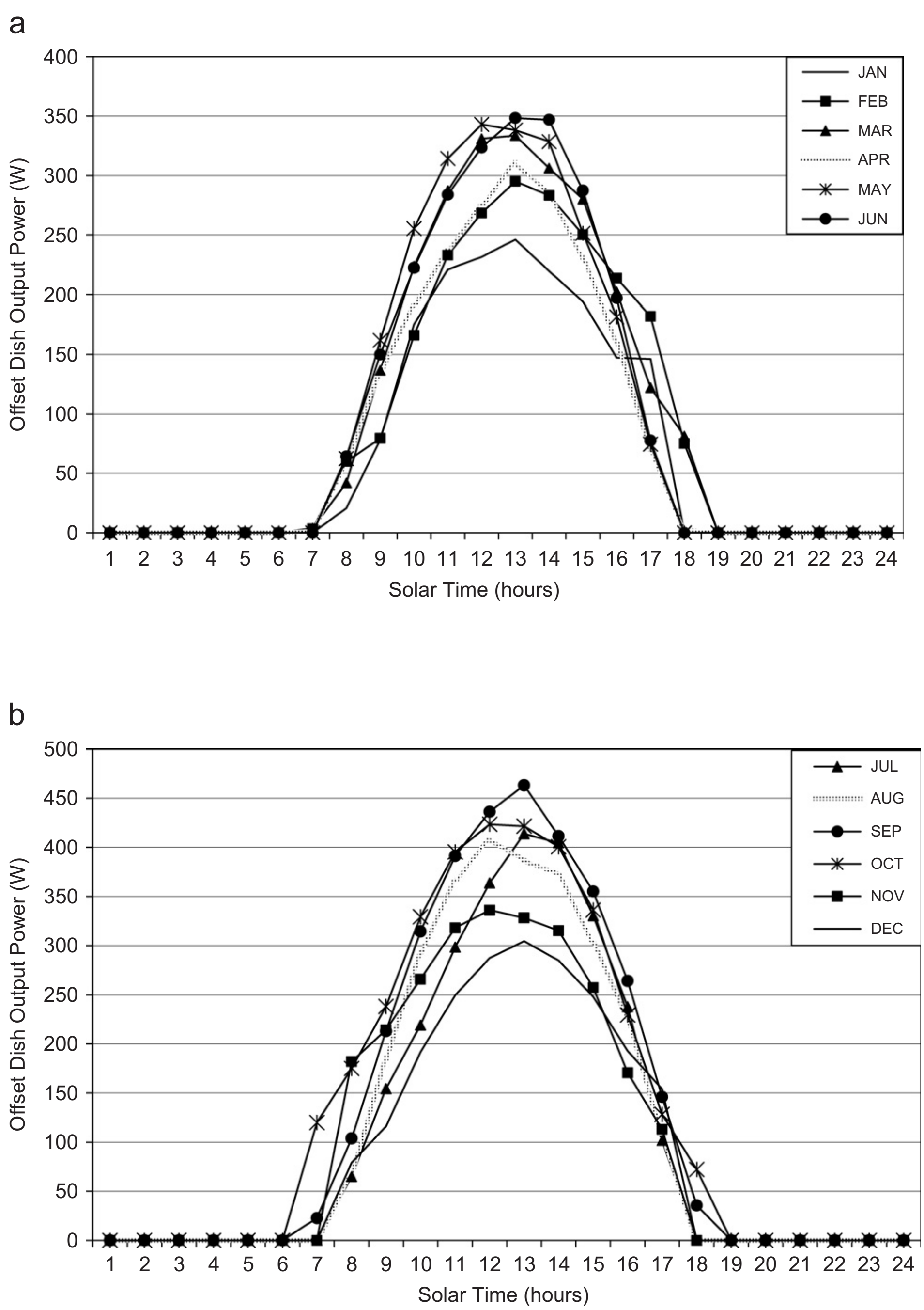


Fig. 5. Monthly average hourly output power for offset paraboloidal dish (W): (a) from January to June and (b) from July to December.

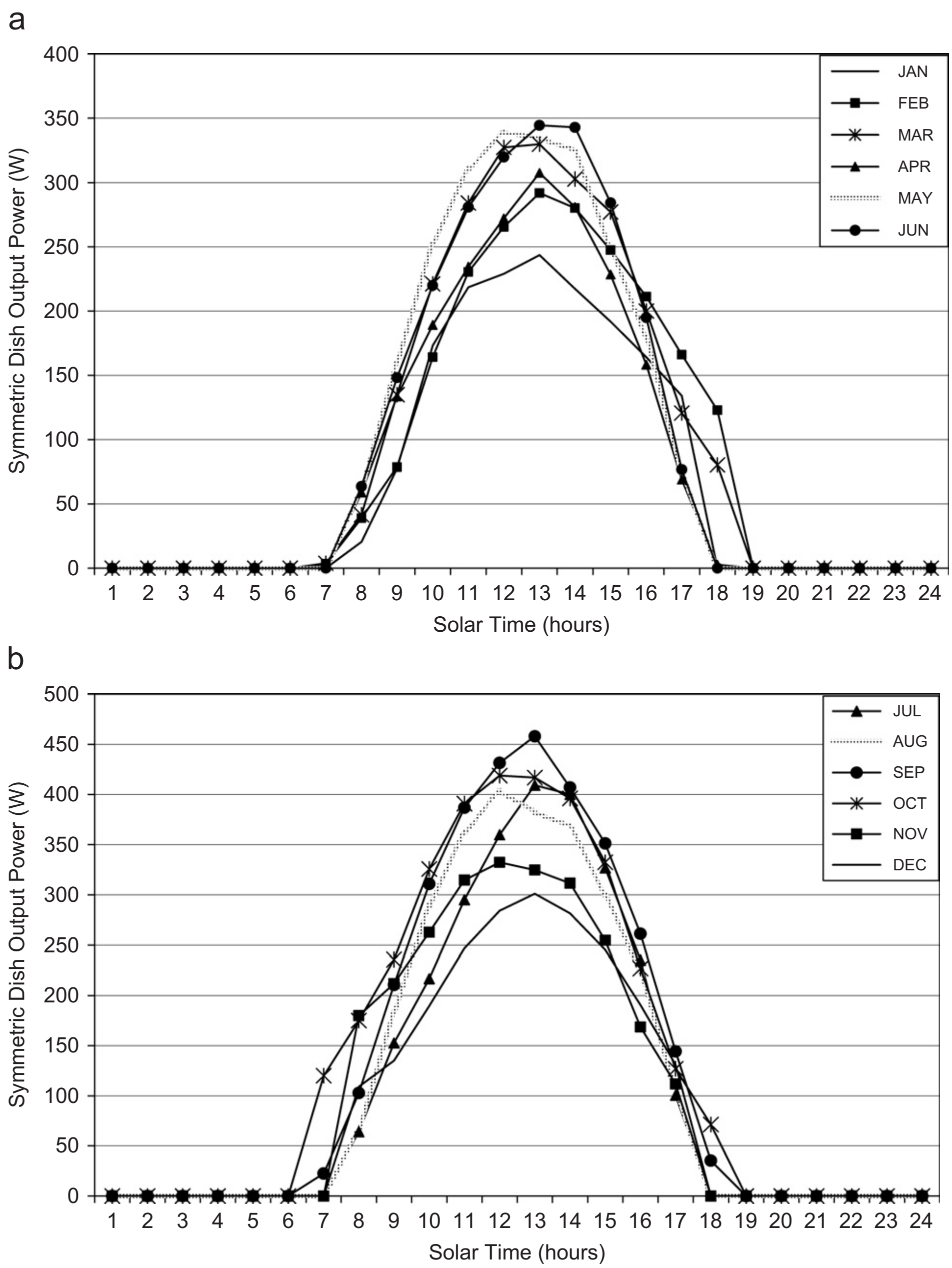


Fig. 6. Monthly average hourly output power for the symmetrical paraboloidal dish (W): (a) from January to June and (b) from July to December.

April, May and June. Correspondingly, the output power can reach 300 W for December; it has values ranging from 300 to 450 for July, August, October, November, and it exceeds 450 for September.

The shading effects for symmetrical paraboloidal dishes decrease the output power from TCSEvOF systems. Although there is no shaded area on the offset paraboloidal dishes, they have less reflective surface for comparing to the symmetrical ones having the same parameters. This missing part causes to diminish obtainable energy. In this study, it was found that offset paraboloidal dish produced much more energy than the symmetrical one when comparing under the same conditions. The difference of monthly average annual obtainable power was calculated as 0.82% using Izmir solar irradiance data. The monthly average annual power gained from the offset paraboloidal dish proposed here was computed as 885.35 kW. Considering the aperture area of the dish offered as 0.85 m^2, it can be estimated that the annual power would be 1041.6 kW/m^2.

At this stage, it can be useful to discuss some economical aspects for the TCSEvOF system proposed. The biggest part of the cost because of the FOB. The light is scattered by Rayleigh dispersion effect at the entrance of the bundle. Besides, it can be absorbed by the holes between the cables. These effects can cause excessive heating and degradation of the PMMA material. To minimize them, two types of

optical fibres that have different diameters (type 1: 2.5 and type2: 3.0 mm) were used to bundle the fibres. Thirty-one pieces of type 2 cables were installed at the centre of the bundle and 64 pieces of type 1 cables were placed surrounding them. The prices of the large core optical fibres are still very high in the market. The cost of type1 is about \$5.78 per metre, and \$8.08 for type 2. The capital cost of the FOB used in this study is about \$1850. Fortunately, operation and maintenance costs are not required. However, it must be protected from humidity and excessive heating to prevent degradation. The other components of the dish processed by chrome and the TCSEvOF system are the sun tracking system with its motors. The dish processed by chrome has a price of about \$71 and the cost of the sun tracking systems with the motors is \$178. The total capital cost of the TCSEvOF system proposed here is about \$2099 for the aperture area of 0.85. Then the total capital cost can be defined as \$2470/m^2 for the dish. The dish is needed to maintain and it may be required to replace a new dish up to 5 years. In addition, the sun tracking system has the operation cost. It uses the electric current even in very low values, voltages as about 13–18 V dc and power consumption in normal case is 200 mA. The TCSEvOF system can be developed by adding some components depending on the aim of the usage.

5. Conclusion

In this paper, studies conducted on the idea of TCSEvOF were reviewed under six important titles listed as characterization of the system, solar lighting, solar surgery, photo-bio reactors, hydrogen generation and photochemical reactions, solar power generation and solar pumped lasers. The mathematical model for symmetrical paraboloidal dish was presented and a new one was derived for offset paraboloidal dish taking into account the dispersion effects. The obtainable output power values from the symmetrical and offset dishes were evaluated by using the data obtained EU-SEI meteorology station. It was compared with the annual output power obtained from the systems. Some economical aspects of the low cost offset paraboloidal dish offered were discussed and its capital and operation costs were defined.

The main deductions, which can be concluded from the results of the present study, can be given as follows:

a. Idea of TCSEvOF has been a source for numerous studies conducted on different areas since the 1980s.
b. It can even meet different types of concentrators such as CPC in the literature depending on the aim of the study; the most common type of concentrators is the paraboloidal one.
c. The importance of optimizing the receiver and dish sizes has been emphasized in order to maximize overall system efficiency and decrease the cost in the literature.
d. While the studies on symmetrical paraboloidal dish systems theoretically or experimentally have been placed in the literature, any study on offset ones were not conducted for the TCSEvOF system.
e. Transmission efficiency of FOB was found as 87% by ignoring the internal and external losses of optical fibres.
f. Optical efficiency of the whole system was calculated as 68% in the optimum condition, but it was found as 63% for the system proposed. It can be deduced that this result is close to the optimum value. Overall system efficiency was found as 59%.
g. It is known that the offset satellite antennas are preferred to symmetrical ones due to the collection of much more energy under the same conditions. This feature was investigated for the TCSEvOF system proposed in the present study. It was found that the offset paraboloidal dish produced much more energy than the symmetrical one when comparing under the same conditions. The difference of monthly average annual obtainable power was calculated as 0.82% using Izmir solar irradiance data.
h. The monthly average annual power gained from the offset paraboloidal dish proposed in here was computed as 885.35 kW. Considering the aperture area of the dish offered as 0.85 m^2, it can be estimated that the annual power would be 1041.6 kW to per square metre.
i. The total capital cost of the TCSEvOF system proposed is about \$2099 for the aperture area of 0.85. Then the total capital cost can be defined as \$2470/m^2 for the dish.

The next steps of this study will be to present the results of the precision of the new sun tracking module and the output power to be obtained from the system experimentally.

At this point, the advantages and disadvantages of the system can be discussed. Offset paraboloidal dishes have some drawbacks. Symmetrical paraboloidal dishes have a more compact shape. Offset paraboloidal dishes should be more modular. For this aim, more reflective materials can be used and the dish can be made smaller. A design that would not disfigure the esthetical structure can be modelled beside functionality. On the other hand, the offset dishes have the receiver controlled easily against negative bending effects. Furthermore, no shaded area results from the receiver on the offset dish.

The chief aim of using FOB is to transport the concentrated solar energy to desirable places. However, the attenuation of the optical cables is considerably high and increases by cable length. For this reason, attention should be paid to the minimum length of FOB in solar energy applications. Otherwise, it can reduce the energy efficiency and raise the system cost.

The type of the optical fibres, plastic, glass or liquid can be chosen for the aim of the study. Glass optical fibres show less attenuation feature than the plastical ones. However, plastical optical fibres are more flexible and can have larger core diameter, and it can be more suitable for solar lighting. On the other hand, the applications of solar

power generation are required at high temperatures and it can be more appropriate to use glass optical fibres. At present, the core diameter of glass optical fibres is very small compared to the plastical ones. Accordingly, great number of cables can be needed to bundle from the glass optical fibres. The holes between the optical fibres should be reduced as much as possible to minimize the losses during the bundling process. It can be provided by forming joining cables hexagonally in the entrance of the FOB or mixing the cables that have different core diameters.

Finally, TCSEvOF systems can have a great potential for solar energy application in a wide range of research area. The systems based on the ideal TCSEvOF can find significant opportunities to be used in some innovative and prospective studies with multidisciplinary research structure.

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